The Bornholm Power System

A Full-Scale Laboatory for Smart Grid Research

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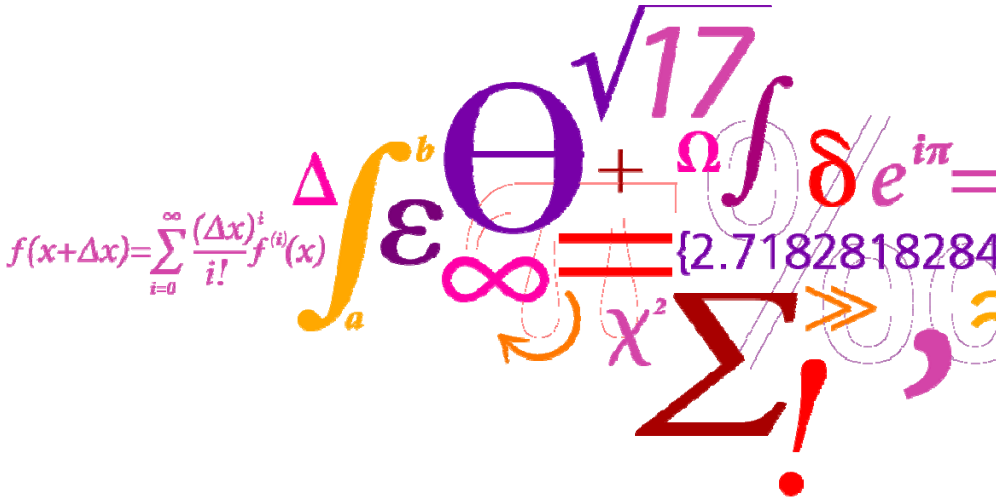
A Full-Scale Laboratory for Smart Grid Research

Prof. Jacob Østergaard
Centre for Electric Technology

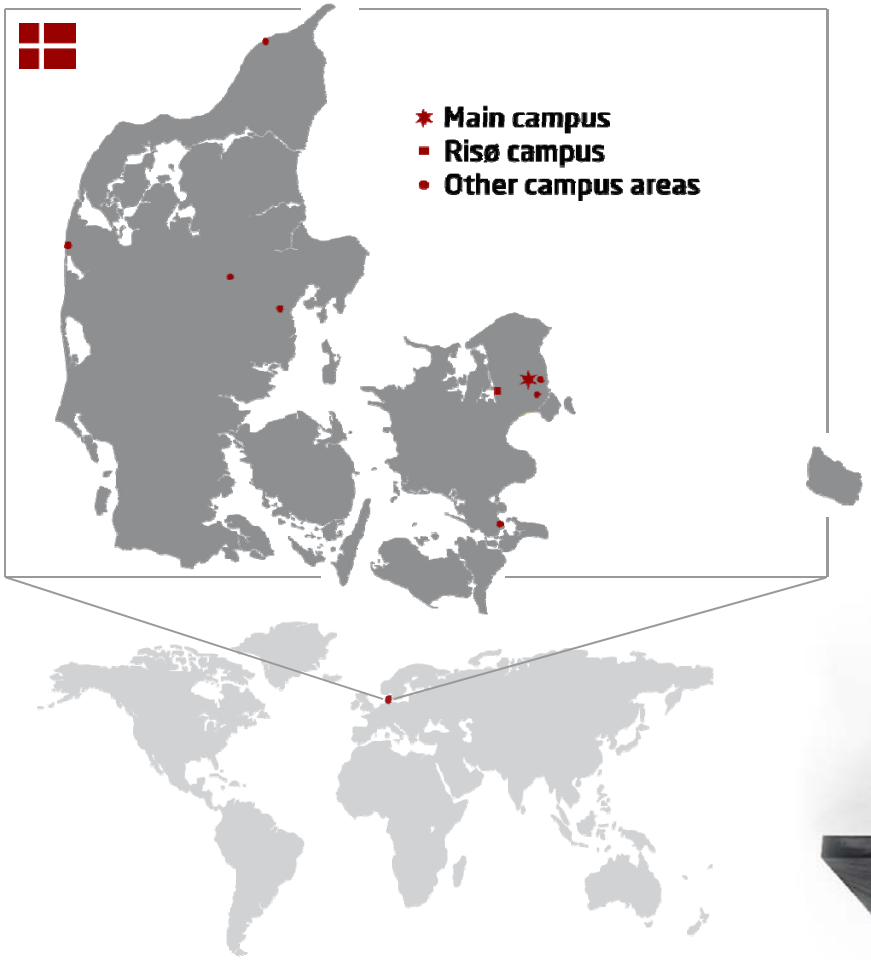
18 October 2011
Workshop @ ETH Zurich



DTU Electrical Engineering
Department of Electrical Engineering

Technical University of Denmark

(founded 1829; first rector H.C. Ørsted)



Key figures

Total students	~8.500
including Ph.D.	1.200
and Int. M.Sc.	650
Research publications	3.600

Ranking

Leiden *Crown Indicator* 2010:

no. 1 in Scandinavia

no. 7 in Europe

Centre for Electric Technology (CET), DTU

- Established 2005
- Research focus
  - Development of a more *intelligent, flexible and automated power system* to handle the future extension with renewable energy and the long-term vision of a fossil-free energy system
- Competences: Electric power engineering (systems+components), automation and ICT
- ~45 researchers (hereof ~20 PhD-students)
- 3 strategic partnerships

ENERGINET.DK DONG energy SIEMENS

- Centre committee
- Visiting professors (currently Prof. Kempton, University of Delaware)
- Collaborations with leading academia (ETH Zürich, HKPoly, UC Berkeley, PNNL, ...)
- 50+ industrial collaboration partners
- 40+ research projects

Extensive National and International Collaboration of CET

PowerLabDK

ABB nkt cables

danskenergi SIEMENS

DONG energy VATTENFALL

ENERGINET.DK Vestas

IBM

IEEE PES Power & Energy Society®

Danish Chapter

Strategic Center Agreements

ENERGINET.DK

DONG energy

SIEMENS

Danish Research Consortium for Wind Energy

Vestas

SIEMENS

...and others

iPower

SPIR

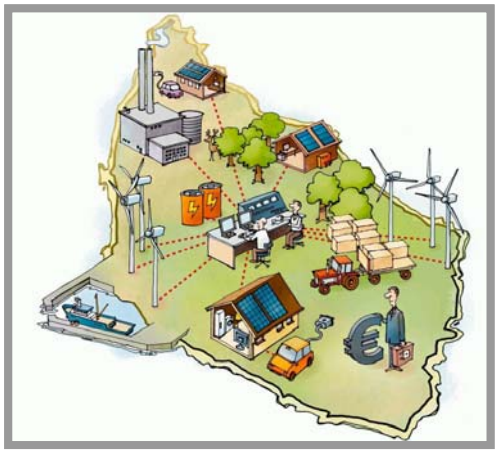
31 Partners including:

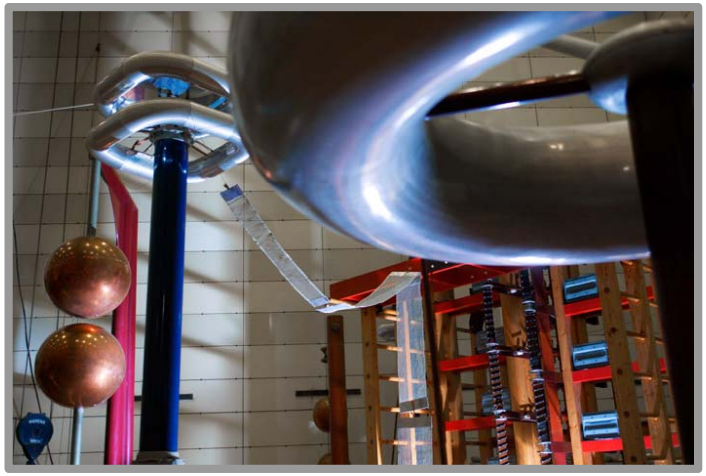
ITRIS

Danfoss IBM

CET Research Focus Areas

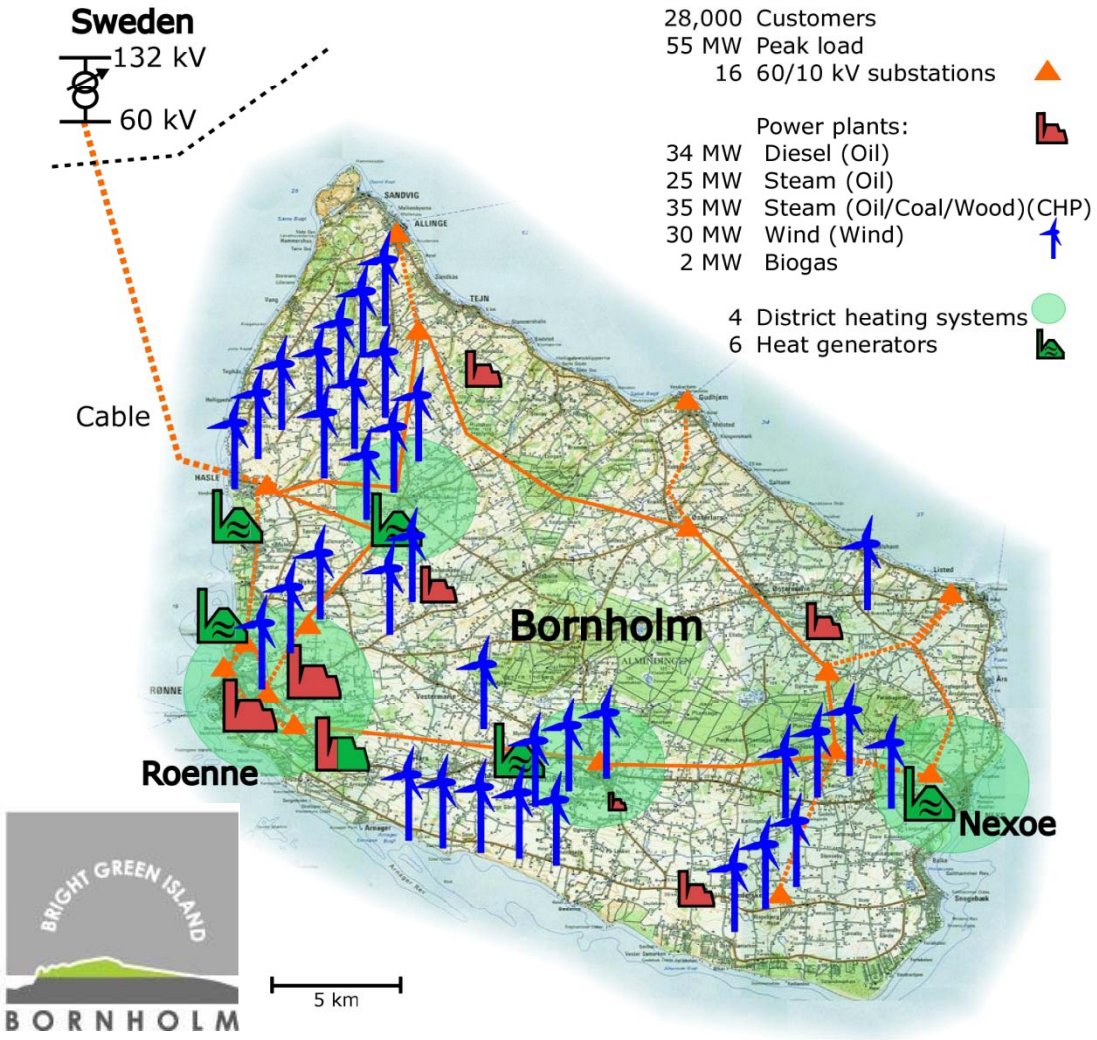
RES+DG Integration / Active Distribution Grids and Markets / Power System Security / Electric Components





Bornholm Full-Scale Laboratory

33% Wind Power Penetration



Strong strategy and political support

BORNHOLM.DK
BRIGHT GREEN ISLAND

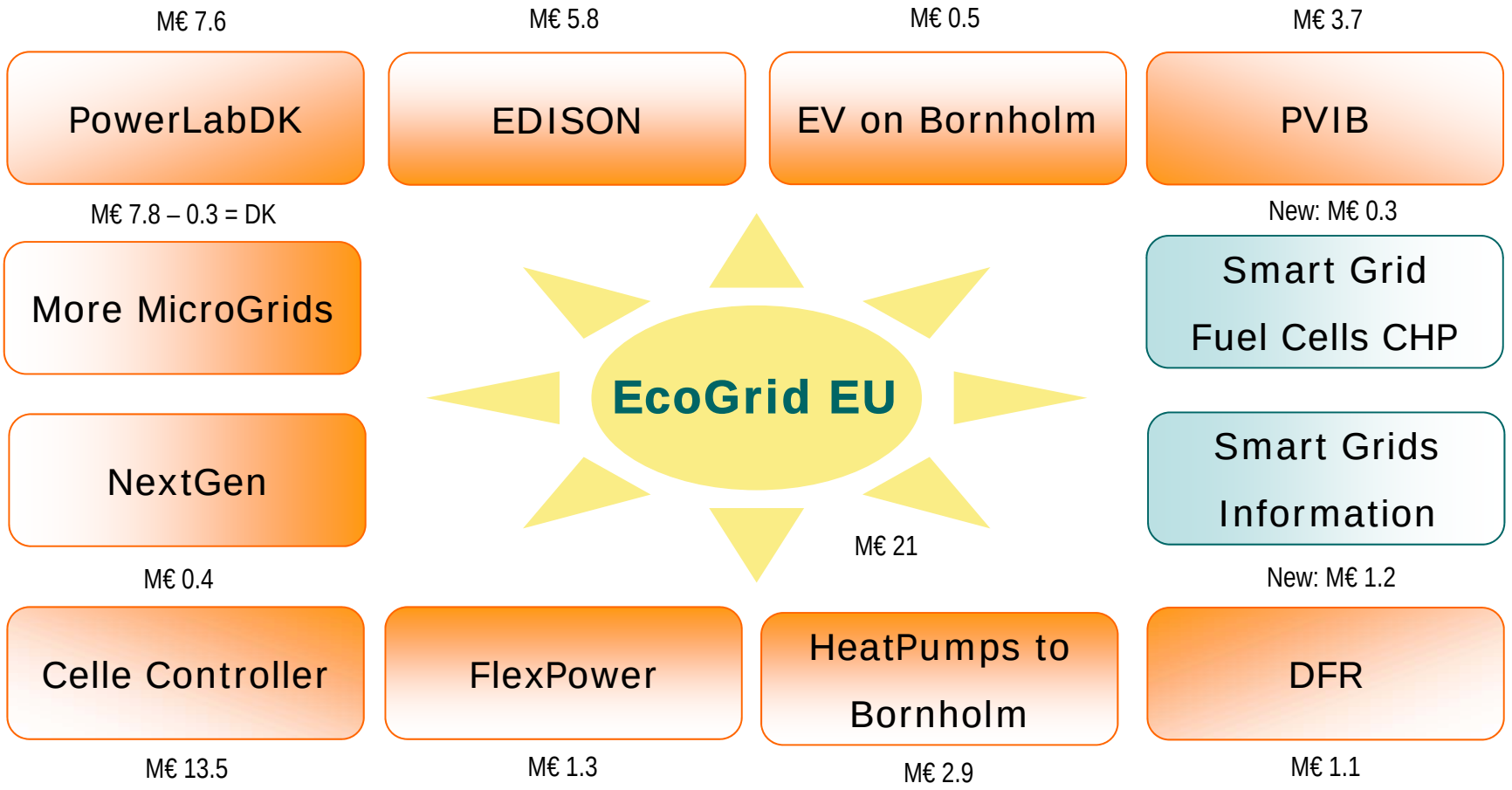
Energy resources
- Customers
- Wind power
- Biogas plant
- CHP-plants
- District heating
- PV roll-out
- eCar roll-out

Nordpool market (DK2)

Key Numbers for Bornholm Power System

Property	Value
Customers	
Number of customers	~28.000
Number of customers (> 100.000 kWh/year)	~300
Total energy consumed	268 GWh
Peak load	55 MW
Low-carbon energy resources	
Wind power plants	30 MW
CHP/biomass	16 MW
PV (roll-out under project)	2.0 MW
Biogas plant	2.0 MW
Electric vehicles (under roll-out)	
Grid	
60 kV grid	131 km
Number of 60/10 kV substations	16
10 kV grid	914 km
Number of 10/0.4 kV substations	1006
0.4 grid	1.887 km
Communication	
Fiber network between 60/10 kV substations	131 km
District heating	
Number of district heating systems	5
Total heat demand (in 2007)	560 GWh
Operation	
Normal operation mode	Interconnected Nordel
Island operation capability	Continuous

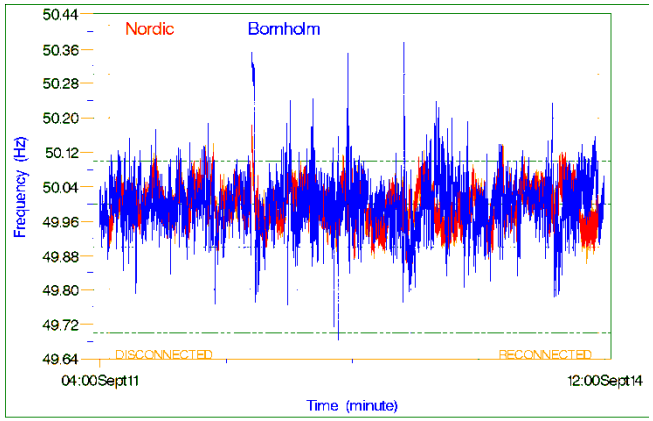
Research and Demonstration Activities at Bornholm

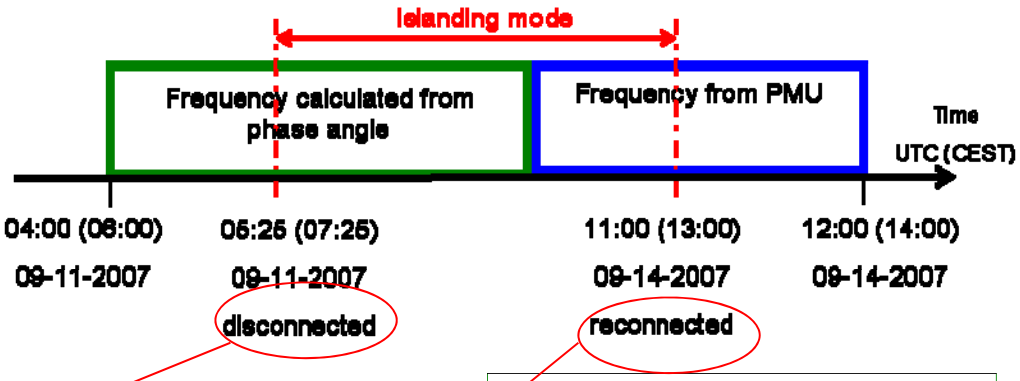


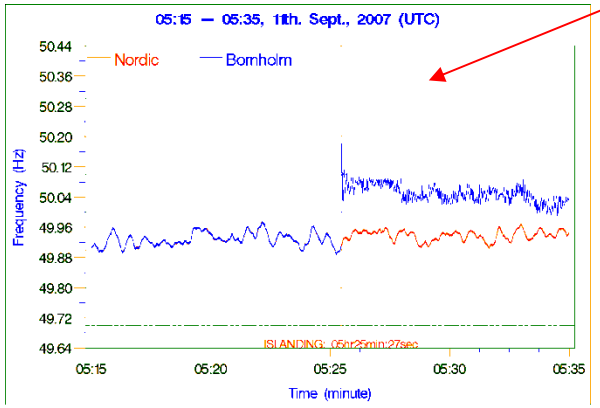
- Some M€ 60 funding of RD&D projects using Bornholm.

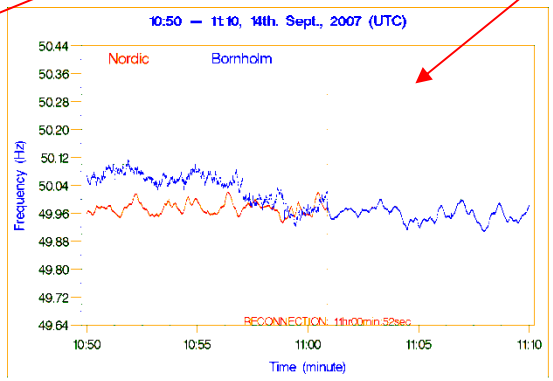
Planned Islanding Test of Bornholm
September 2007

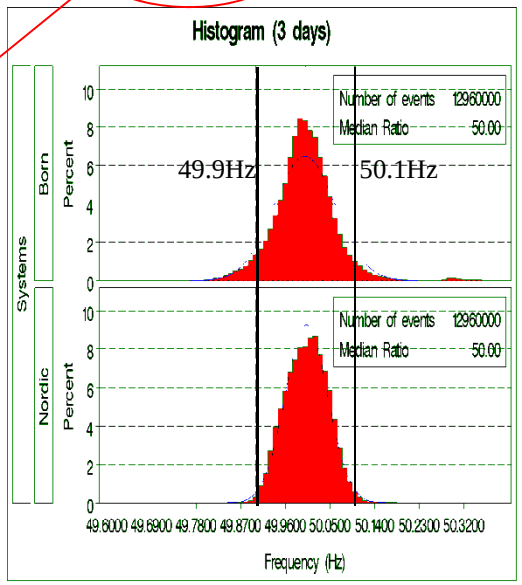
EU FP6
More Microgrids



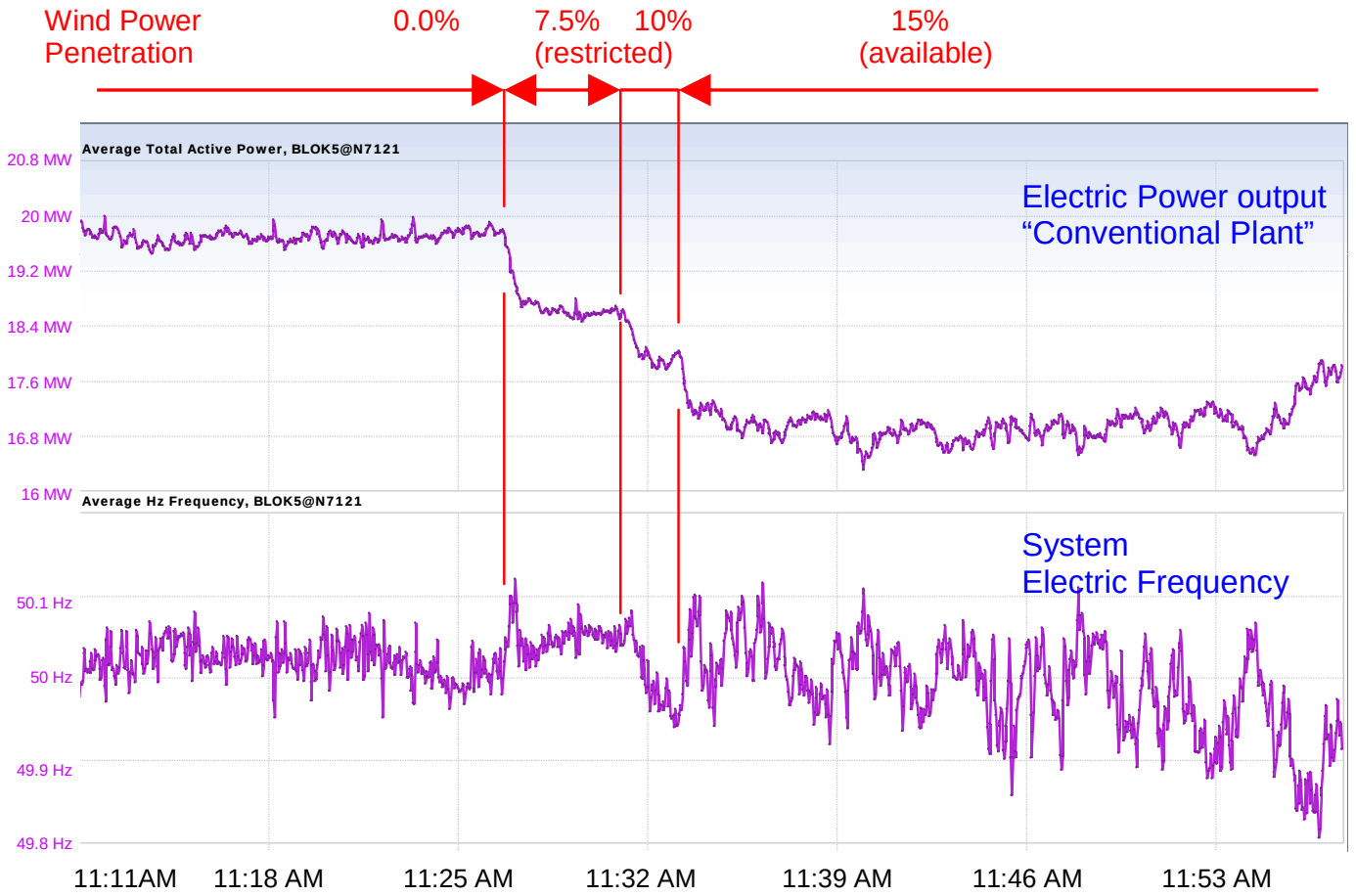








Bornholm Islanding Test
17 September 2009

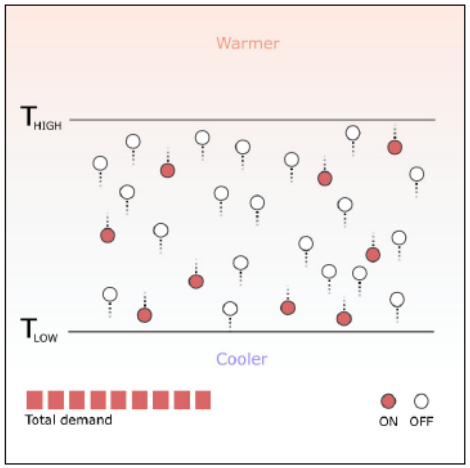


Acknowledgement: Germán C. Tarnowski & John Eli Nielsen.

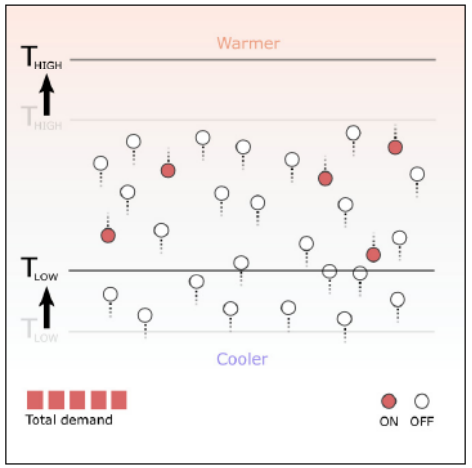
Demand as Frequency Controlled Reserve

- Large share of the demand can be disconnected in a short period wo. problems
  - heat
  - cooling
  - pumping
  - EV charing
  - …

Grid frequency at 50Hz



Grid frequency **falls below** 50Hz



$$T_{high} = T_{high}^{normal} - kf\,(f - f_0)$$

$$T_{low} = T_{low}^{normal} - kf\,(f - f_0)$$

Ref: IEEE Transaction on Power Systems, 2011

Projektet er støttet af Forskel-programmet.

Statistical Representation of Frequency Response

Measurements in Laboratory

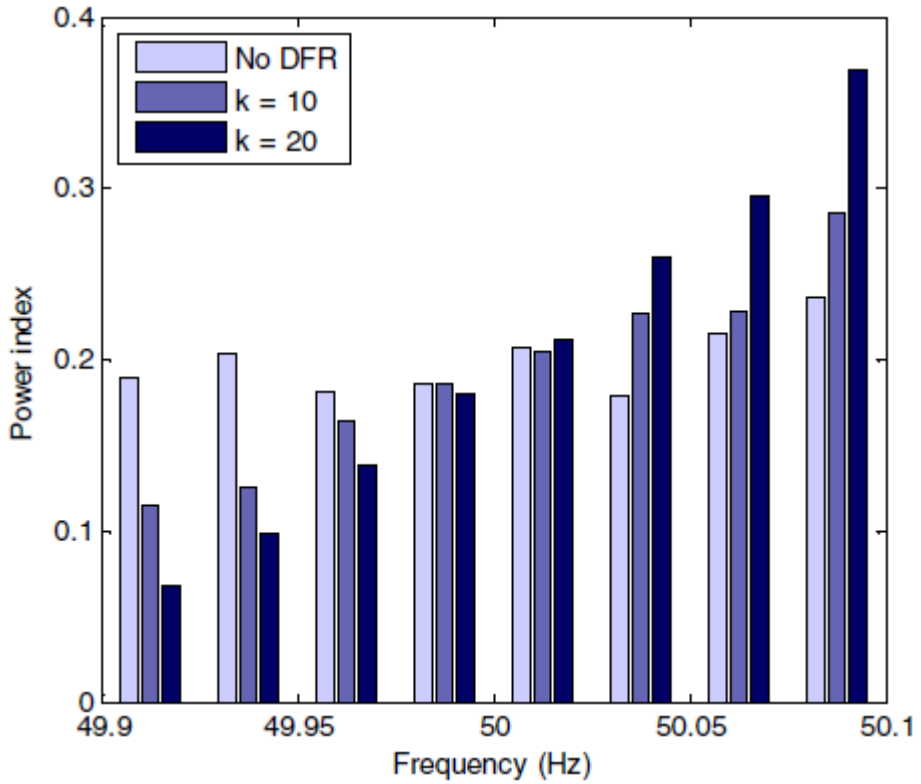
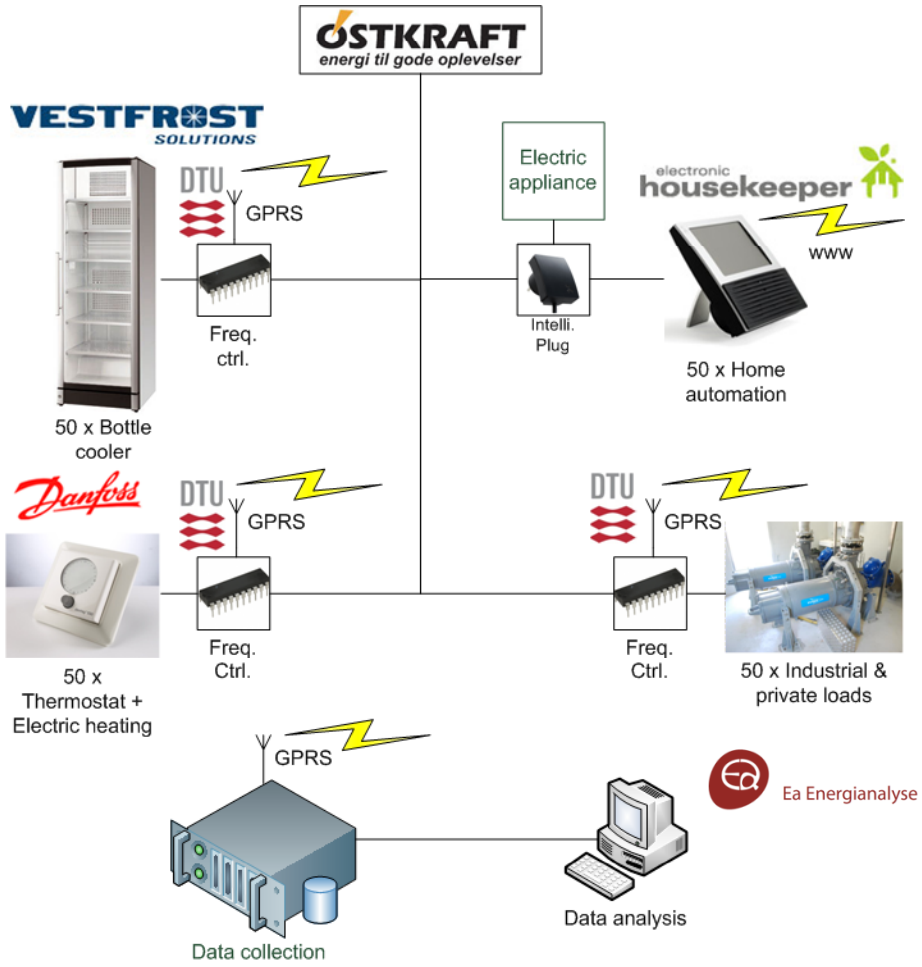


Fig. 9. Statistical representation of DFR response in 25 mHz frequency slots. Different values of k clearly impact the slope of the frequency response.

Field Test with 200 Frequency Controlled Demand Units



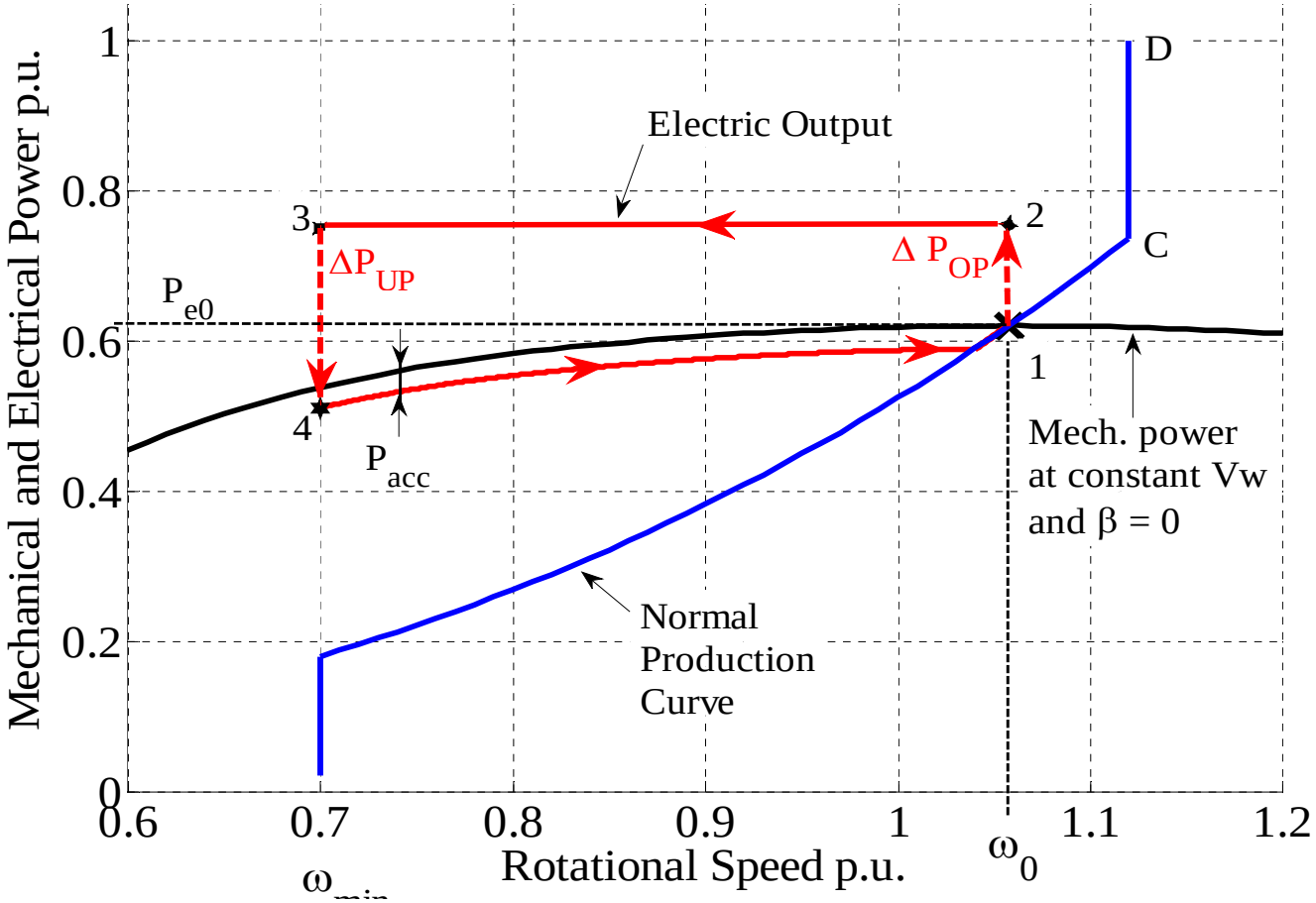
- Frequency reserves (2008)
  - 22.000 €/MW/år (in DK2)
  - 8.000 €/MW/år (in DK1)
- Price per unit 20 €
  - Simple pay-pack time = **1-2½ year** (w/1 kW unit)

Ref: IEEE Transaction on Power Systems, 2011

Projektet er støttet af EUDP-programmet.

Over-production Operation

Modern Variable Speed Wind Turbines

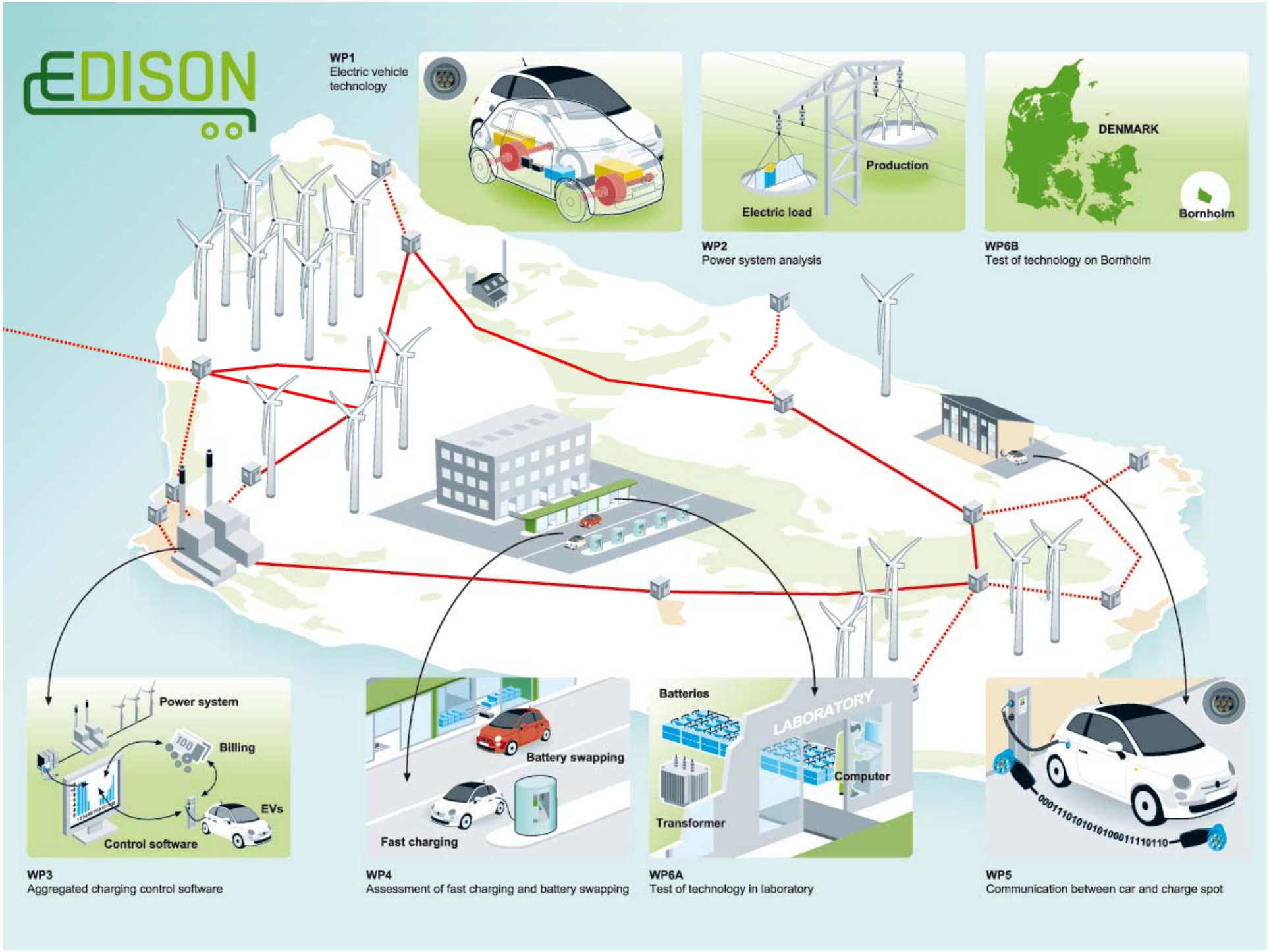


Ref: Patent WO/2011/000531

Energy Storage Technologies

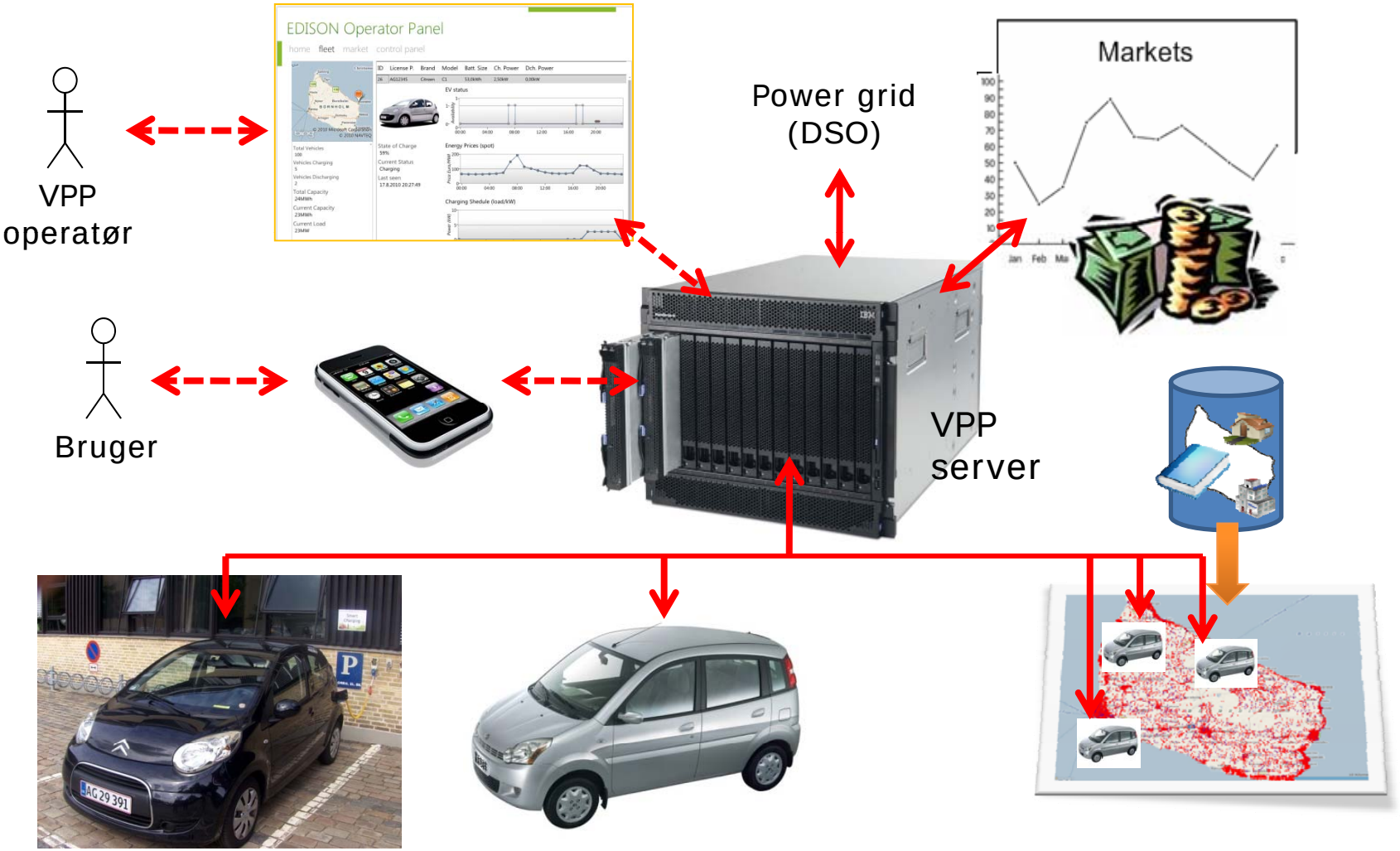
Source: Prof. Kempton

Technology	Application	Installed Cost $/kWh
Pumped Hydro	ISO Services Wind Integration	310 – 380
Compressed Air	ISO Services Wind Integration	81 – 102
Sodium–sulfur battery (NaS)	Grid Support Wind Integration	650 – 700
Lead Acid Battery	Grid Support ISO Services	505 – 760
Flow Battery	Grid Support ISO Services	470 – 1125
Li-ion Battery	ISO & DSO Services PV Integration	1050 – 1550
Fly Wheel	ISO Services	7800 – 7900
Grid-integrated-Vehicle with V2G	ISO services DSO services	13

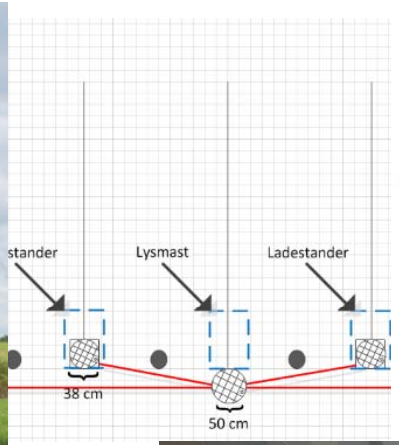

EDISON
WP1
Electric vehicle technology
Production
Electric load
WP2
Power system analysis
DENMARK
Bornholm
WP6B
Test of technology on Bornholm
Power system
Billing
EVs
Control software
WP3
Aggregated charging control software
Battery swapping
Fast charging
WP4
Assessment of fast charging and battery swapping
Batteries
LABORATORY
Computer
Transformer
WP6A
Test of technology in laboratory
WP5
Communication between car and charge spot

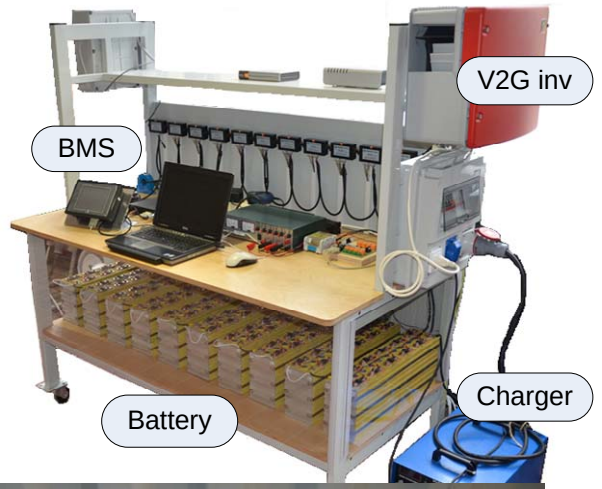
Virtual Power Plants

Aggregation of Distributed Energy Ressources in the Electricity Market and the Grid



Intelligent System Integration of Electric Vehicle

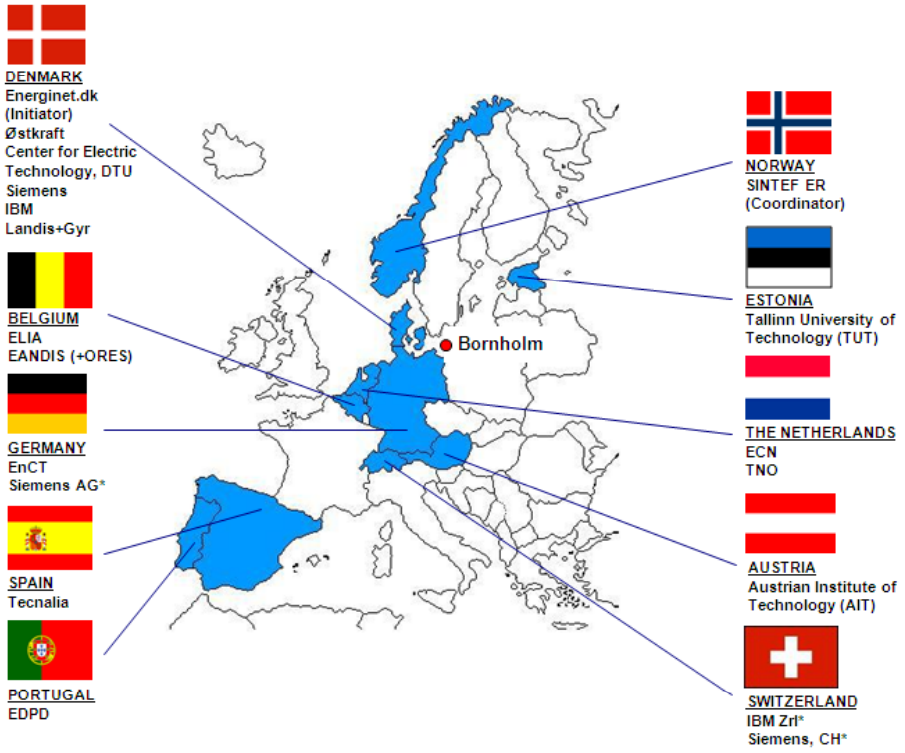




EcoGrid EU

Large-scale demonstration of the future intelligent distribution system

- EU FP7 ENERGY
- 2011-14
- Integrated research and demonstration
- 2,000 active customers
- EU fast-track to Smart Grids
- Budget: ~22 million Euro



* Third Party

BRIGHT GREEN ISLAND
BORNHOLM

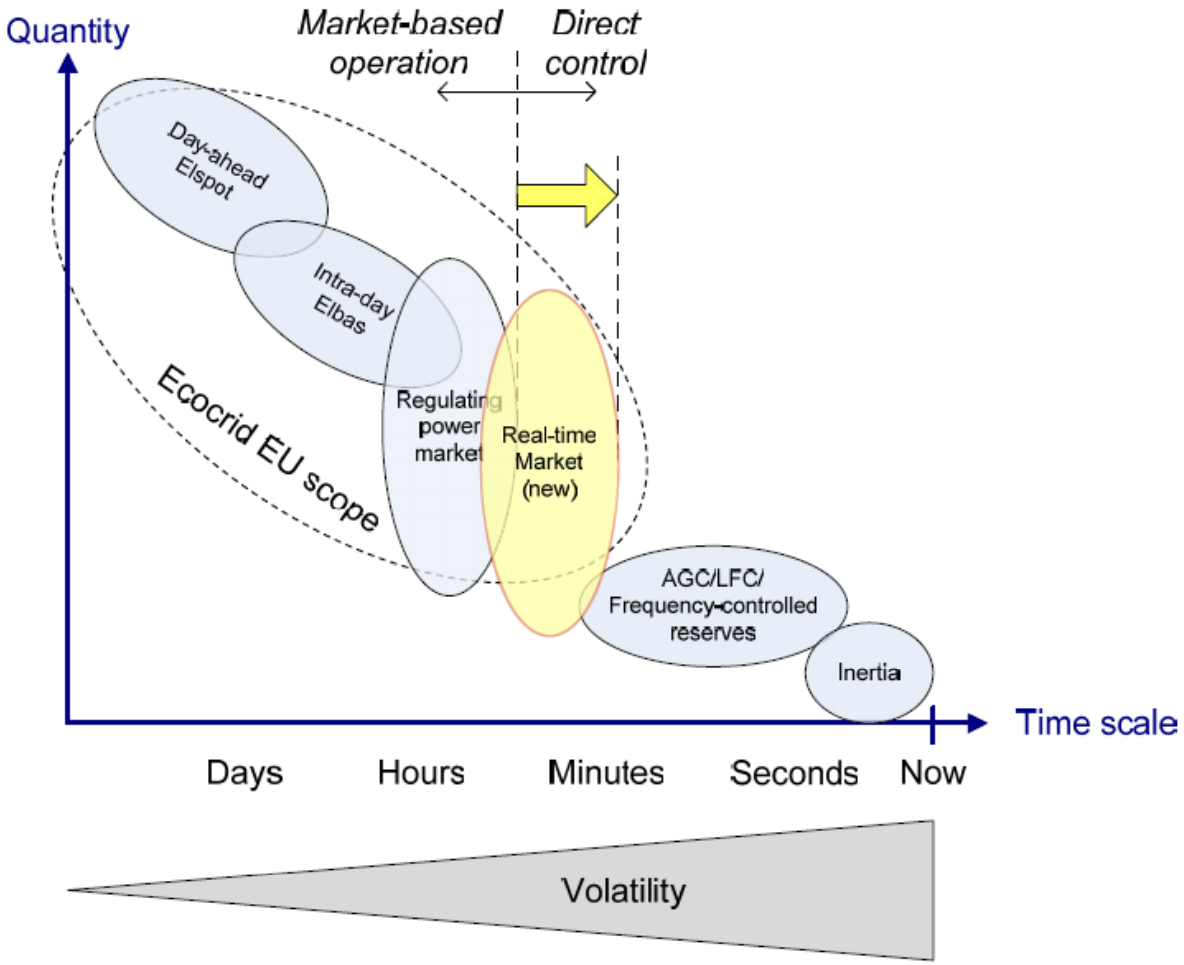
COOPERATION

Why Do We Need a New Real-Time Market?

1. More wind -> less predictability
   - Calls for market clearing near the time of delivery
2. More wind -> more fluctuation
   - Calls for markets with higher time resolution
3. Less dispatchable generation
   - Calls for demand-side participation
4. Increased use of electricity for heat and transportation
   - Calls for local congestion management

Extention of the Market Solutions

Small Units, Small Time Constants, Near Real-Time



Comparison with the Nordic Regulating Power Market

- **Regulating power market**
- Market resolution: 1 hour
- Submit bids no later than 45 mins before each hour
- Full response in less than 15 minutes
- Sustain response for up to 1 hour
- Works well with hydro power, thermal power plants and gas engines

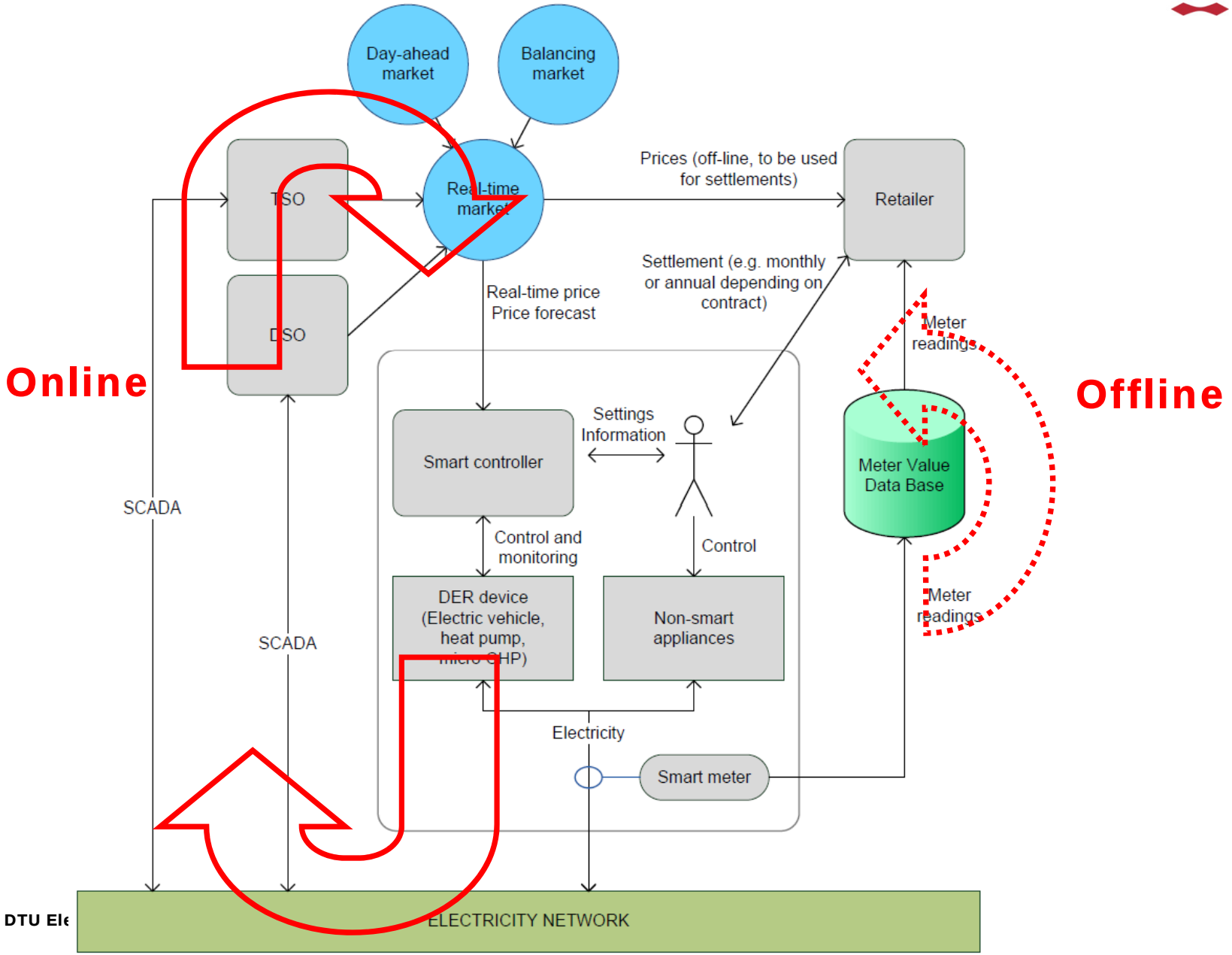
- **Real-time market**
- Market resolution: 5 minutes
- No bids
- Price takes effect immediately
- No promises made
- Works well with loads, wind and micro-generation

Conventional Market Process

1. Submit bids
2. Find supply/demand curve intersection
3. Publish price and schedules -> first settlement
4. Ex post: compare facts and schedules
5. Final settlement (incentive to keep schedule and bid true cost/utility)

Real-Time Market Process

1. Predict supply and demand curves
2. Set price
3. Publish price (price is the final settlement price)
4. Monitor response, update forecasts, back to 1


Day-ahead market
Balancing market
TSO
Real-time market
Prices (off-line, to be used for settlements)
Retailer
DSO
Real-time price
Price forecast
Settlement (e.g. monthly or annual depending on contract)
Meter readings
Online
Offline
Smart controller
Settings
Information
Meter Value Data Base
SCADA
Control and monitoring
Control
DER device (Electric vehicle, heat pump, micro CHP)
Non-smart appliances
Meter readings
SCADA
Electricity
Smart meter
ELECTRICITY NETWORK

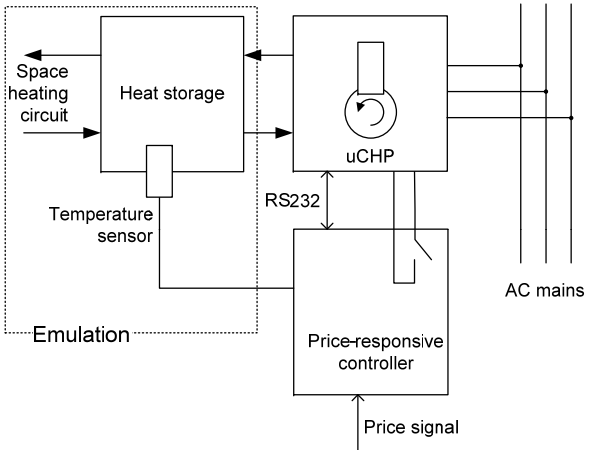
FAQ

- Should customers respond to price updates every 5 minutes?
  - Not necessarily, automatic controllers will handle that.
  - Manual response customers may be notified in case of e.g. extreme prices
- Will the customers experience reduced comfort?
  - It depends. Customers get a chance to adapt their level of comfort to their willingness to pay
- Will the real-time price be higher or lower than the “classic” price?
  - On average they will be the same for a non-responding customer
  - Responding customers get a chance to utilise low prices and reduce the bill
- Is the purpose to reduce electricity consumption?
  - No, but it may be a side effect of increased attention
  - But the bill will be reduced for responding customers

Real-Time Market

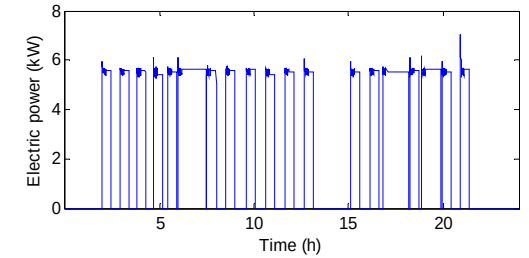
Control-by-prices Tested in Laboratory

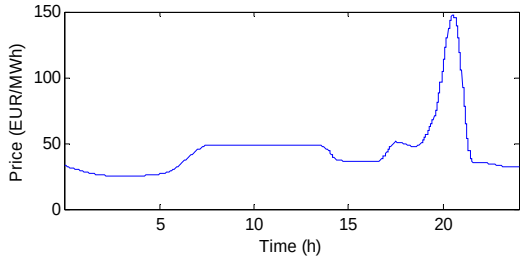
Lab. setup:

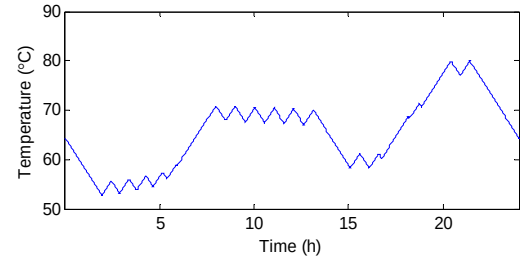


Elec. gen,	5 kW
Heat gen.	10.5 kW
Heat demand (constant)	5.25 kW
Storage	750 liter
Min. temp.	50 °C
Max. temp.	80 °C

Measuements:







Increased income = **7.3 %**
wo/ comfort changes (and very simple algorithm)

Ref: IEEE Transaction on SmartGrids, 2011.

Power System Balancing Purely by DER and Flexible Demand

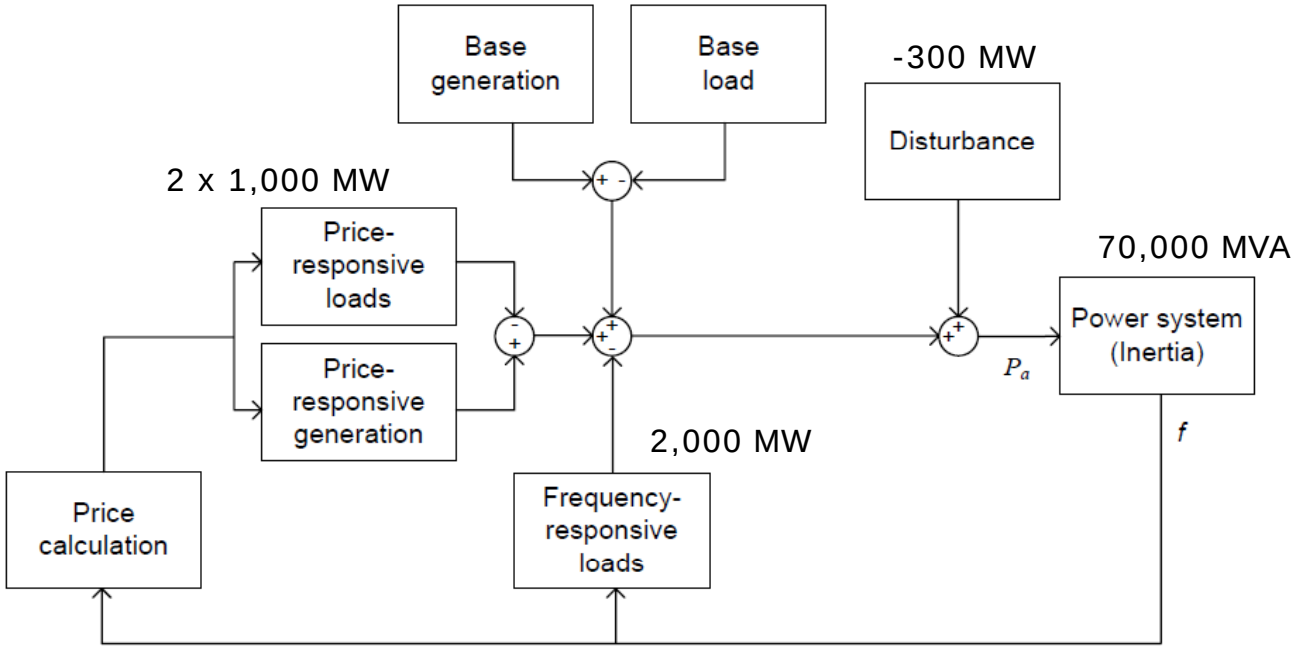
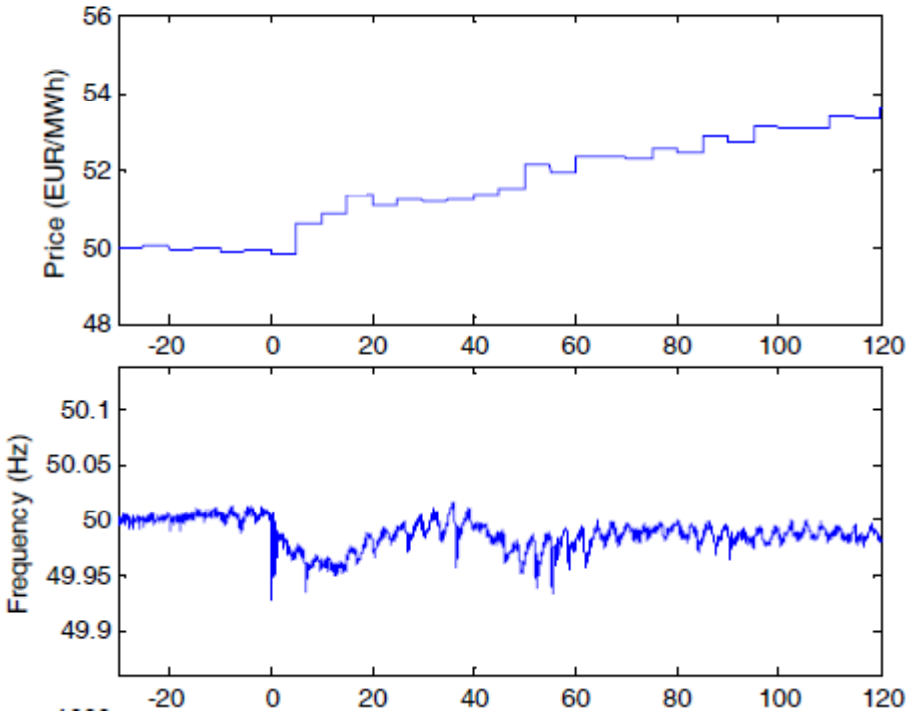
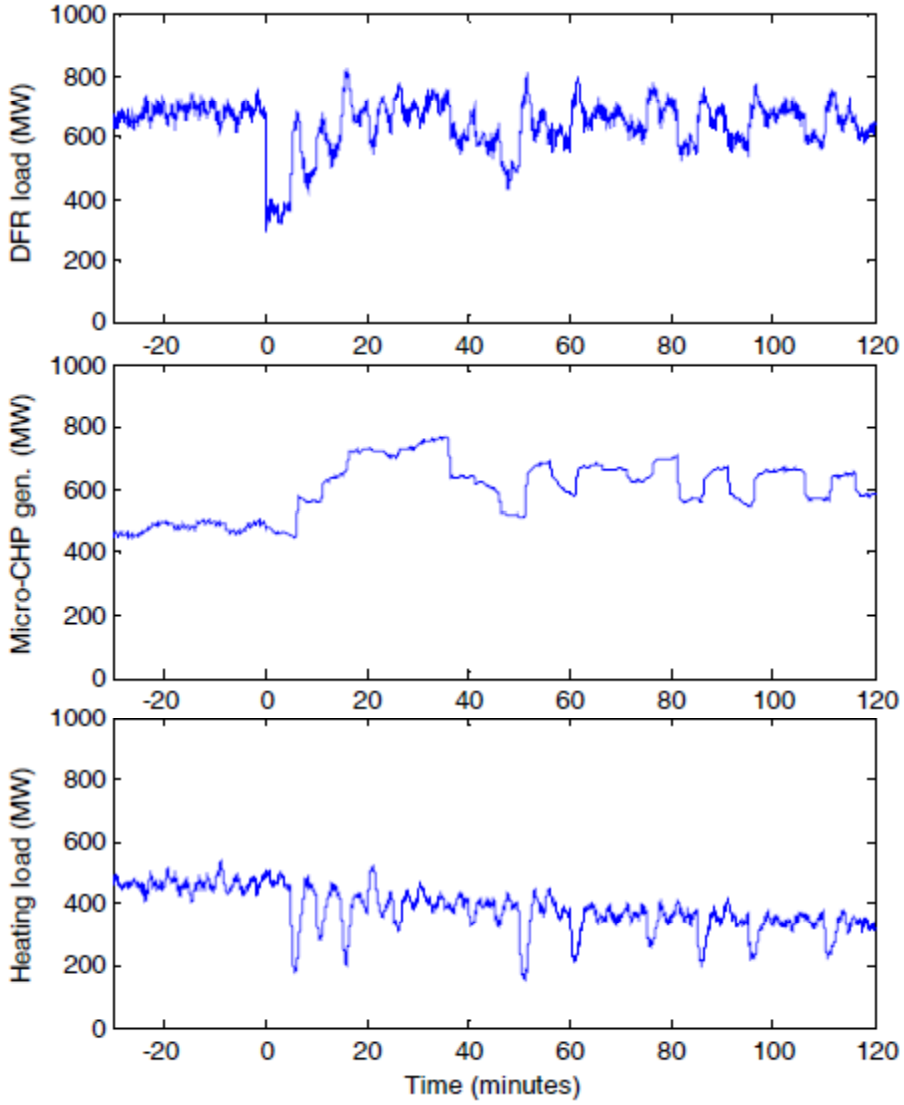


Fig. 1. System control scheme overview.

System response @ 300 MW loss of generation

Simulation Based on Lab Verified Sub-Models





Not a new idea…
Homeostatic Utility Control by Prof. Schweppe from 1980

- In 1980 Prof. Schweppe publish a vision for a future power system
  - Fred Schweppe et al., "Homeostatic Utility Control", *IEEE Transactions on Power Appartus and Systems*, Vol. PAS-99, No. 3, May-June 1980, pp. 1151-1163

- Homeostasis
  - Property of a system that regulates its internal environment and tends to maintain a stable, constant condition, typically used to refer to a living organism. Multiple dynamic equilibrium adjustment and regulation mechanisms make homeostasis possible.

- Idea of a electric energy system based on flow of:
  - Power
  - Money
  - Information

Bornholm and PowerLabDK

Experimental Platform for Electric Power and Energy

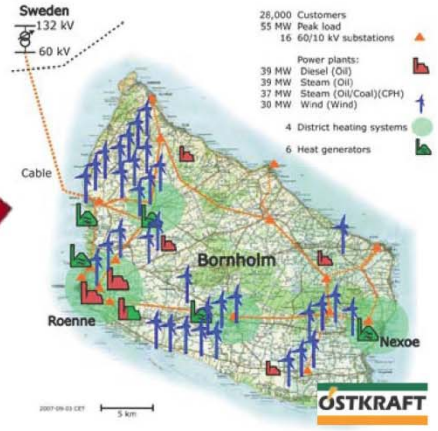
IHK (high-power)

DTU Elektro building 329

Flexible multi-purpose research laboratory

Large-scale test system

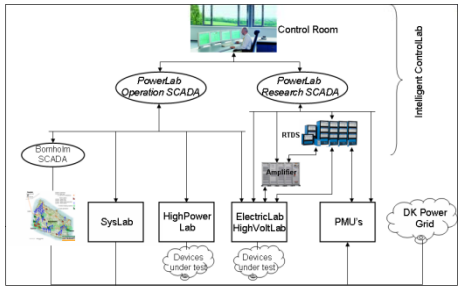
Risø DTU (SysLab)



Full-scale power system

Østkraft (Bornholm)

- Integrated experim.



- Stakeholders:

ABB, nkt cables, danskenergi, SIEMENS, DONG energy, VATTENFALL, ENERGINET.DK, Vestas, IBM

- Budget:
  18 million Euro
- Stakeholder funding:
  4+ million Euro

PowerLabDK

Experimental Platform for Electric Power and Energy

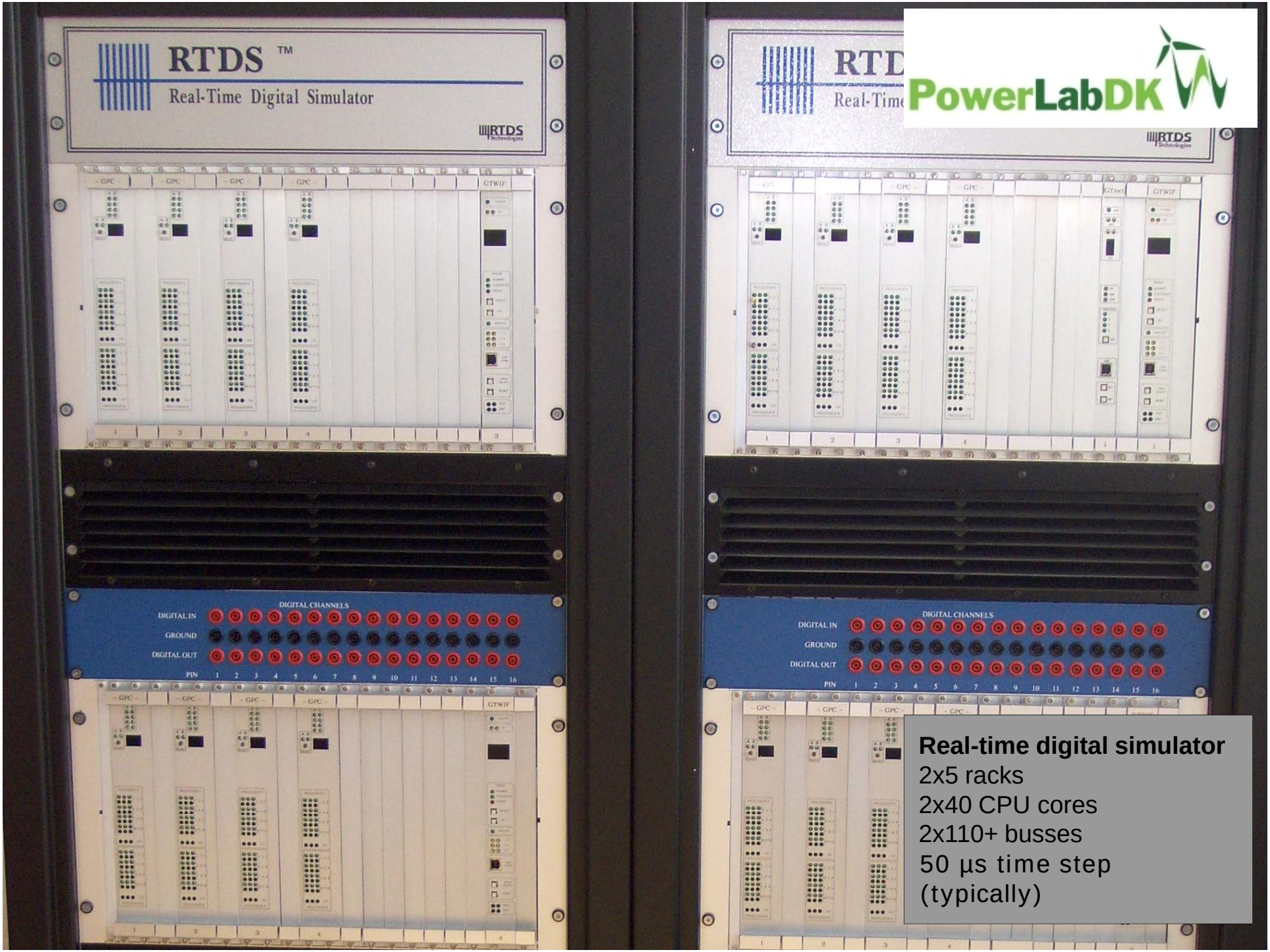
A vision with high ambitions

– Unique facilities supporting research which is difficult or impossible to undertake in existing/conventional facilities

– Full-range from component research to large real-life experiments , and from research to development, test and demonstration

– Open and accessible and support collaboration

– International hub for smart grid development


RTDS ™
Real-Time Digital Simulator
RTDS Technologies
DIGITAL CHANNELS
DIGITAL IN
GROUND
DIGITAL OUT
PIN 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
GTWIF
PowerLabDK
Real-time digital simulator
2x5 racks
2x40 CPU cores
2x110+ busses
50 µs time step
(typically)


PowerLabDK
4 Quadrant Amplifier
150 kW (continously)
300 kW (5 minutes)
DC to 5 kHz (-3 dB)
50 kHz (small signals)
Slew rate: > 52 V/µs

Second-to-None Test-bed for Power System Control and Operation

Control room, SCADA, RTDS and Hardware-in-Loop

Fully equipped control room

Online

SCADA system

Online data/ control

Europe's most powerful real-time digital simulator

Models

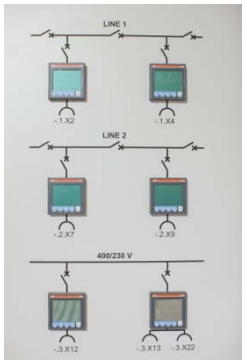
Online data

A I/O

150 kW (300 kW) amplifier

Power

Grid in lab with 22 “substations”



Power

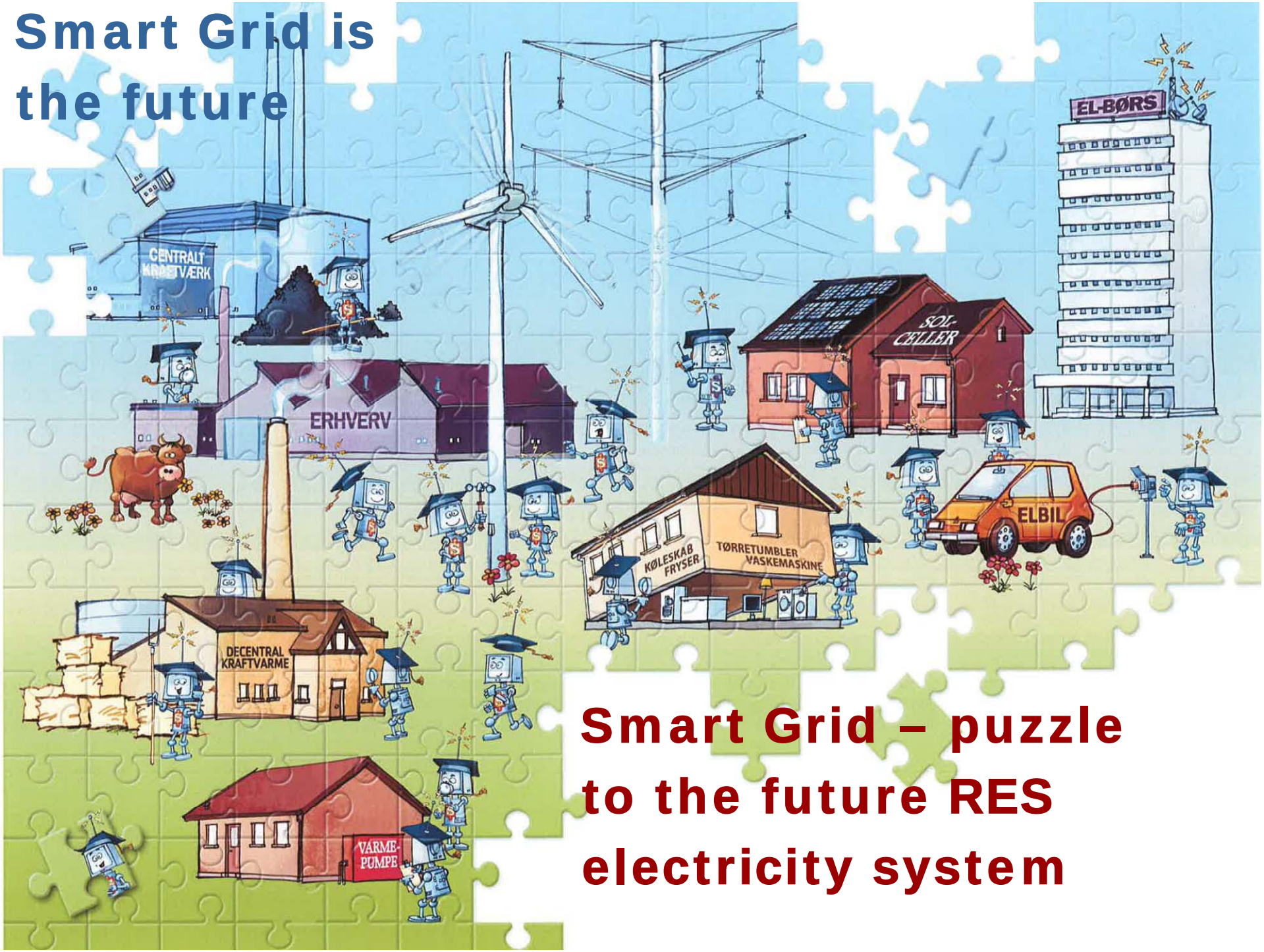
Online data/control

IBM blade center (VPP etc.)

Online data/control

Lab experiments (device /system under test)

Smart Grid is the future



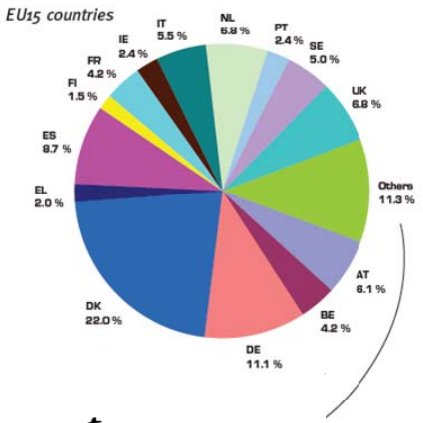
Smart Grid – puzzle to the future RES electricity system

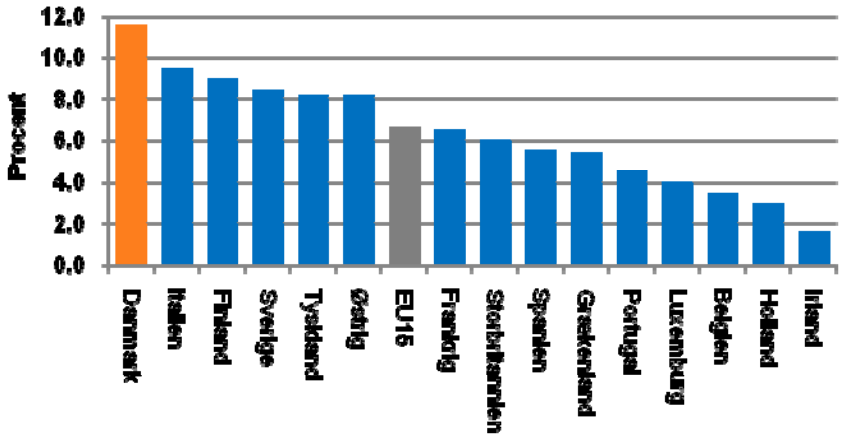
DK Government Policy

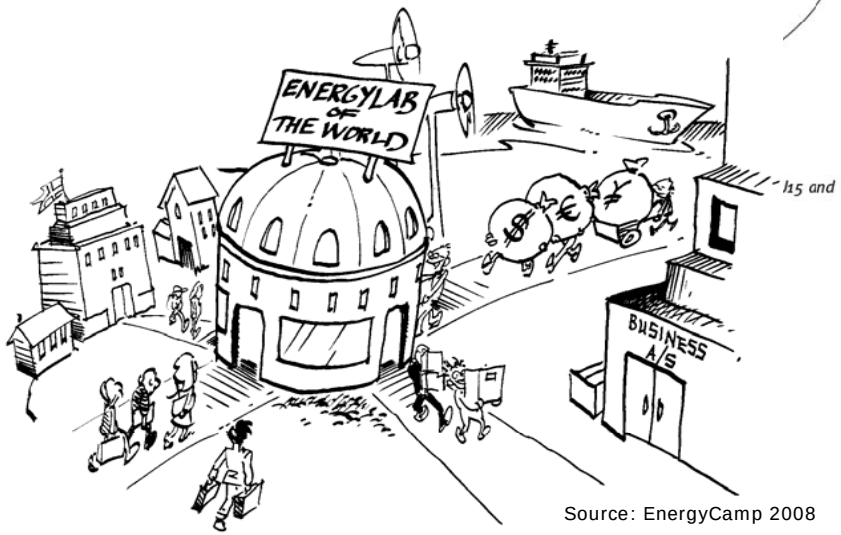
- 2020
  - 40% reduction of GHG emission (compared to 1990)
  - 50% wind power penetration (yearly average) in the electricity system
- 2035
  - 100% RES penetration in the electricity & heating systems
- 2050
  - 100% RES penetration in the energy system

Danmark as a “First Mover”

- Within SmartGrids DK has potential for an international leading position, which can drive a large green growth (jobs and export)
  - Unique energy system (experience, data and knowledge)
  - Substantial R&D-level
  - Strong DK energy industry
  - Consensus on Smart Grid as priority area (government, industry, research)







Source: EnergyCamp 2008

Smart Grid Network of the Danish Minister of Climate and Energy

9 main recommendations & 35 specific recommendations

1. Price signals to end-customers which provide value to demand flexibility
2. New economic regulatory framework for grid companies smart grid activities
3. Taxes which support an efficient electrification
4. Efficient activation of storage and distributed generation
5. Strengthen standardisation and iteroperability
6. Research as dynamo for green growth
7. Strengthen end-customers awareness
8. Minimize risks of end-customers and other actors
9. Make it easier to offer new services

Contributions

Thank you!

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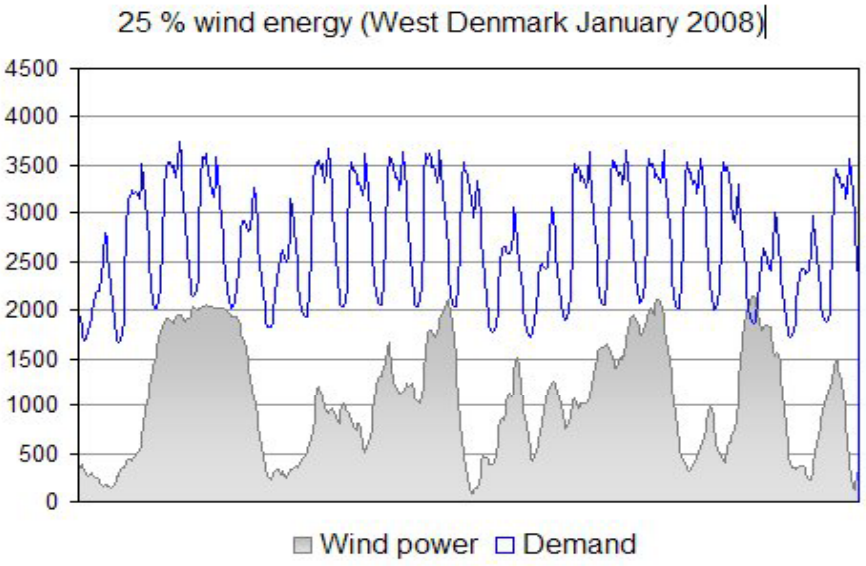
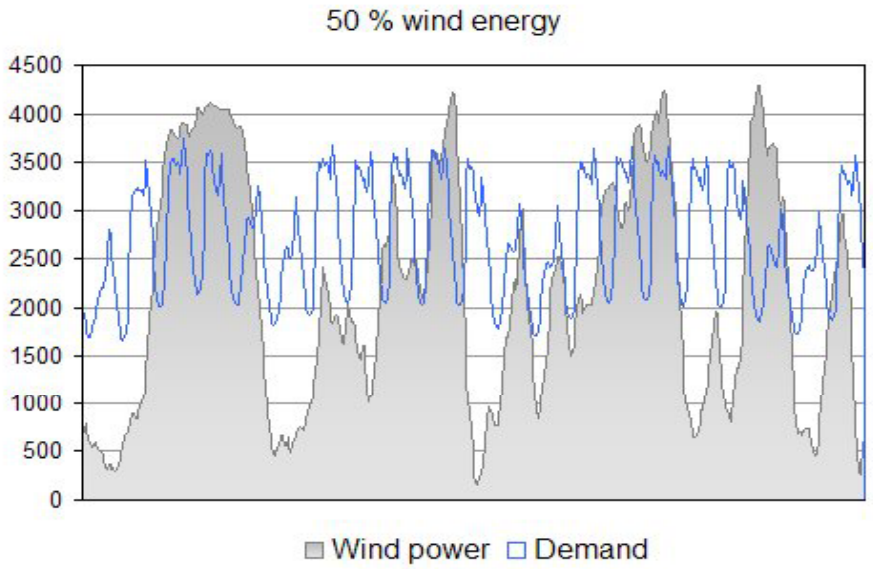
Extra

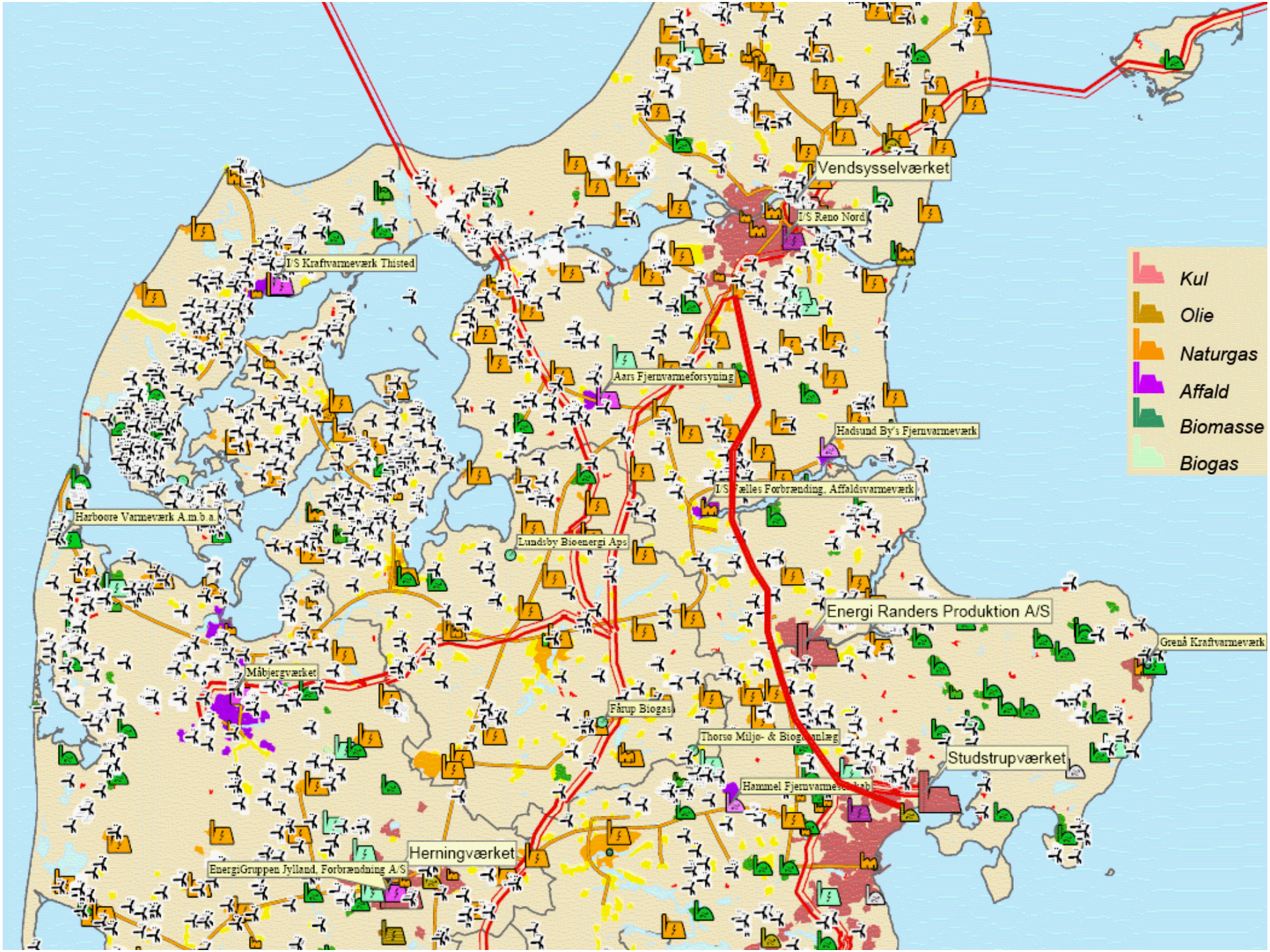
The Danish Wind Power Case



Wind power covers the entire demand for electricity in 200 hours (West DK)



In the future wind power will exceed demand in more than 1,000 hours


Vendsysselværket
I/S Reno Nord
I/S Kraftvarmeværk Thisted
Aars Fjernvarmeforsyning
Hadsund By's Fjernvarmeværk
I/S Fælles Forbrænding, Affaldsvarmeværk
Harboore Varmeværk A.m.b.a.
Lundsby Bioenergi Aps
Energi Randers Produktion A/S
Grenå Kraftvarmeværk
Måbjergværket
Fårup Biogas
Thorsø Miljø- & Biogasanlæg
Studstrupværket
Hammel Fjernvarmeselskab
Herningværket
EnergiGruppen Jylland, Forbrænding A/S
Kul
Olie
Naturgas
Affald
Biomasse
Biogas

Abstract

- The Bornholm power system is a Danish distribution system with 33% wind power penetration (yearly average). The distribution system has 28,000 customers and a peak load of 55 MW. The Bornholm power system is part of the Nordic interconnected power system and power market, and it has many of the characteristics of a typical Danish distribution system. The system can be operated isolated from the transmission grid. The Bornholm power system, which is linked with the laboratories at Technical University of Denmark (DTU), is used for a wide number of research activities on smart grid technologies. The research activities are driven by the ambitious Danish targets regarding integration of renewable energy (100% renewable energy in 2050). In the presentation the Bornholm power system will be introduced and examples of the research results involving wind power, demand side and new market designs at Bornholm will be provided. Also the new large European project, EcoGrid EU, focusing on large scale smart grid demonstration on Bornholm will be introduced.

CV of Prof. Jacob Østergaard

- Since 2005 Jacob Østergaard has been Professor in Electric Power Engineering and head of Centre of Electric Technology (CET) at Department of Electrical Engineering at Technical University of Denmark. Earlier he has been employed 10 years in industry at Research Institute of Danish Electric Utilities, DEFU. His research focuses on intelligent electric power systems especially new network and control architectures, integration of distributed generation and renewable energy sources and increased flexibility via active demand. He is responsible for leading the center to its present state with 50 staff members and development of the Bornholm power system into an unique experimental platform. He serves in several boards and organizations, including chair of the Danish experimental platform PowerLabDK, chair of the IEEE PES Danish chapter, member of the Advisory Council for the European technology platform SmartGrids and member of the Smart Grid advisory network of the Danish Minister of Energy and Climate.